# Chapter 5
# Angle and Distance Observations--Theodolites, Total Stations, and EDM

## 5-1. Scope

This chapter describes the field procedures for measuring angles with precision theodolites and measuring distances using electronic distance measurement (EDM) systems. Both these operations are now combined using electronic total stations.



**Figure 5-1. AGA Geodimeter Model 220 electro-optical distance meter mounted in Wild tribrach force-centered into rigid concrete instrument pedestal.**

## 5-2. Instrument and Reflector Centering Procedures

*a. General.* Accurate centering of instruments, reflectors, or tribrachs, over the monument reference marks (as illustrated in Figure 5-1) is a critical procedure for collecting deformation measurements. Specifications for instrument/prism centering are presented below for tribrach optical plummets, nadir plummets, and forced centering.

*b. Built-in optical plummet.* Tribrach centering procedures apply to equipment with an optical plummet incorporated in the instrument or with a detachable tribrach that will rigidly attach to the instrument.

(1) Calibration. Tribrach optical plummets shall be calibrated at the beginning of each project using the procedures outlined in the manufacturer's manual. Failure to perform, certify, and record this

calibration process can be grounds for rejecting all subsequent data obtained with an uncalibrated tribrach.

(2) Tolerances. Tribrachs shall be collimated over the object point mark to an accuracy of ± 1mm using the built-in optical plummet. Tripod heads shall be aligned as nearly horizontal as is possible prior to final centering procedures.

(3) Leveling. Final tribrach leveling and centering shall be performed using a level vial from either a mounted theodolite or a standard Wild target. The built-in circular level bubble is not considered accurate enough for this process and should only be used for rough tripod head alignment. All centering leveling vials should be calibrated at the beginning of each project and this fact recorded.

(4) Equipment mounting. Once the tripods and tribrachs have been accurately centered over each end of the line, then the instrument and reflector may be inserted into the tribrachs without further adjustment. Extreme care shall be taken to avoid disturbing the tribrach during the insertion and measurement process.

(5) Check observations. Upon completion of all observations from a particular tripod, a final level and centering check shall be performed to insure no movement has occurred during this process. If significant movement is detected during this final check, then the entire observation process shall be repeated.

*c. Nadir plummet.* A Nadir plummet (Figure 4-2) can be used for centering instead of the tribrach optical plummet. A nadir plummet is precision centering device with a built-in automatic level for use in vertical sighting and collimation. Some models have the capability to define the plumbline to 1 part in 200,000. These plummets have up to five (5) times greater magnification than the optical plummet supplied with the standard Wild-type tribrach. The station reference mark (no larger than 1 mm in diameter), may need to be artificially illuminated under low light conditions for optimal viewing under this increased magnification. Nadir plummet centering should be conducted as follows.

(1) After the tripod is setup over the reference mark, the tripod head is leveled as closely as possible in two perpendicular directions using a tribrach with a Wild-type target and its sensitive level bubble.

(2) Once the tribrach is leveled, the nadir plummet is exchanged with the target in the tribrach and then precisely centered over the mark by a series of fine translation adjustments of the tribrach.

(3) Final collimation is confirmed by observing the mark under rotation in four perpendicular directions about the plummet axis and by re-observing the tribrach level in two perpendicular directions with the target level vial.

*d. Forced centering.* The highest centering accuracies can be achieved using forced centering techniques. A centering uncertainty of 0.1 mm/m can be expected for trivet/pillar plate combinations, permanent threaded pins, and machined sleeve-type insert pins. If possible, both the instrument and reflector should be mounted by forced-centering.

(1) Forced centering pins. Threaded pins on pillars will be used in forced centering mode. Tribrachs with standard target level vials may be used to level tribrachs directly on threaded pins or over plugs.

(2) Tribrach and tripod combinations.  With tripods, standard Wild-type tribrachs should be used as a forced centering mount.  Interchangeable tribrachs shall be used such that the instrument or reflector may be readily exchanged without affecting centering of the tripod/tribrach mount.

(3) Reflector rods.  Threaded aluminum rods for direct insert in monitoring plugs may be used to support reflectors.  When reflector rods are screwed directly into grouted plugs, the same rod shall be used for each successive project survey.  Therefore, the rod number should be recorded so that the same rod is always used at a particular plug.  Reflector HI should be kept as low as possible in order to minimize the effects of potential non-verticality of the rods.

*e. Instrument stability.*  In precise surveys, towers, stands, and tripods must be substantial.  The use of driven stakes or some type of quick setting cement or dental plaster for tripod leg support may be required.  Catwalks that provide support away from tripod legs may be necessary under some soil or platform conditions to ensure that the instrument/reflector is unaffected by nearby motion.  Use of fixed pillars is always prefered over less-rigid tripods, if possible.

## 5-3.  Angle and Direction Observations

*a. General.*  When using an optical or electronic  theodolite for angle measurement, it will be accurately plumbed over the occupied point by either forced centering, attaching the theodolite to the point with a tribrach, or using a tripod and tribrach with an optical plummet, as applicable.

*b. Specifications.*  The following specifications are provided for angle and direction observations:

(1) Repetitions.  Both horizontal and zenith angles will be observed in at least four sets.  The instrument will be re-centered and re-leveled between each set.  With well designed targets and proper methodology, an angle measurement accuracy of 1" is possible with precision electronic theodolites if four sets of observations are taken in two positions of the telescope.

(2) Double centering.  Face left and face right (direct and reverse) point and reads will be made for all targets in all theodolite work.  The requirement of two positions must always be followed in order to eliminate errors caused by mechanical misalignment of the theodolite's axial system.

(3) Reading precision.  All horizontal and vertical circle readings will be recorded to 0.1 arc second.

(4) Horizon closure.  For each station pair (i.e., angle between the backsight and foresight), the method of observing independent angles will be used.  A full set will consist of a direct angle measurement and a separate horizon closure angle measurement.  Their sum will be taken to find the closure to 360 degrees.

(5) Parallax.  Sighting parallax shall be minimized during each pointing operation.  The reticule should be focused first and then the objective lens.

(6) Magnification.  The theodolite shall have a minimum telescope magnification of 30 times or better.

(7) Leveling sensitivity.  Theodolites shall have a plate level vial with a sensitivity of 20 seconds per 2 mm graduation or better.  Once measurements are made, the level of the instrument will be checked.  If found to be greater than 10 seconds, the measurements will be repeated with a leveled instrument.

When using an electronic theodolite and bi-axial compensator, the instrument will be leveled within 2 minutes of arc.

(8) Observing conditions.  Avoid measurements close to any surface that has a different temperature than the surrounding air (walls of structures or soil exposed to the sun's radiation, walls of deep tunnels, etc.).  If any suspicion of refraction influence arises, the surveys should be repeated in different conditions in order to randomize its effect.  Ideally, observations should be limited to days when the weather conditions are fairly neutral (e.g., cloudy day with a light breeze).  Days with temperature extremes should be avoided.  If the instrument must be used when the temperature is hot, then it should be protected from the sun by an umbrella.

*c. Data reduction procedures*.  Angles collected by the method of repeated sets will be reduced to a mean value using the station adjustment technique (see example below).

(1) Mean value.  For each sighted direction in the set, determine the face-left and face-right mean direction value, starting with the backsight observation.

(2) Reduced value.  Subtract the initial or backsight circle reading from the mean direction value of the foresight in the measurement set (backsight value will then be reduced to zero).

(3) Independent sets.  Repeat the above procedures for each of the four independent direct angle sets and calculate the mean value for each direction,

(4) Horizon closure.  Repeat each of  the above steps for each corresponding horizon closure angle set.

(5) Closure correction.  Difference the sum of the means of the direct and closure sets from 360 degrees.  Distribute the misclosure equally to correct the final mean reduced value from each set.  The general form for the misclosure is expressed as:

$$W = 360° - ( \beta_d + \beta_c )$$

(Eq 5-1)

where
$W$ = horizon misclosure
$\beta_d$ = mean direct angle
$\beta_c$ = mean closure angle

and the correction value is determined as:

$$C = W / 2$$

where
$C$ = correction value
$W$ = horizon misclosure

*d. Example data reductions.*  The station adjustment procedure for reduction of horizontal angles is demonstrated in the following example.

SET 1: Direct

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 1 | 0-0-30.0 | 0-0-38.6 | 0-0-34.3 | 0-0-00.0 |
| 2 | 3-0-36.6 | 3-0-40.8 | 3-0-38.7 | 3-0-04.4 |

Reduced Mean Value = **3-0-04.4**

SET 1: Closure

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 2 | 0-0-30.0 | 0-0-38.6 | 0-0-34.3 | 0-0-00.0 |
| 1 | 357-0-25.4 | 357-0-27.2 | 357-0-26.3 | 356-59-52.0 |

Reduced Mean Value = **356-59-52.0**

SET 2: Direct

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 1 | 0-0-30.0 | 0-0-34.4 | 0-0-32.2 | 0-0-00.0 |
| 2 | 3-0-38.4 | 3-0-40.8 | 3-0-39.6 | 3-0-07.4 |

Reduced Mean Value = **3-0-07.4**

SET 2: Closure

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 2 | 0-0-30.0 | 0-0-34.4 | 0-0-32.2 | 0-0-00.0 |
| 1 | 357-0-26.4 | 357-0-26.8 | 357-0-26.6 | 356-59-54.4 |

Reduced Mean Value = **356-59-54.4**

SET 3: Direct

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 1 | 0-0-30.0 | 0-0-37.4 | 0-0-33.7 | 0-0-00.0 |
| 2 | 3-0-40.6 | 3-0-43.0 | 3-0-41.8 | 3-0-08.1 |

Reduced Mean Value = **3-0-08.1**

SET 3: Closure

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 2 | 0-0-30.0 | 0-0-34.2 | 0-0-32.1 | 0-0-00.0 |
| 1 | 357-0-23.3 | 357-0-26.5 | 357-0-24.9 | 356-59-52.8 |

Reduced Mean Value = **356-59-52.8**

SET 4: Direct

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 1 | 0-0-30.0 | 0-0-32.2 | 0-0-31.1 | 0-0-00.0 |
| 2 | 3-0-36.3 | 3-0-38.5 | 3-0-37.4 | 3-0-06.3 |

Reduced Mean Value = **3-0-06.3**

SET 4: Closure

| PT | FL | FR | Mean | Reduced |
|----|------|------|--------|---------|
| 2 | 0-0-30.0 | 0-0-35.2 | 0-0-32.6 | 0-0-00.0 |
| 1 | 357-0-24.2 | 357-0-25.8 | 357-0-25.0 | 356-59-52.4 |

Reduced Mean Value = **356-59-52.4**

Resulting in the following reduced values:

Direct Mean value = **3-0-06.6**
Closure Mean value = **356-59-52.9**

Misclosure = 360 - ( 359-59-59.5 )
Horizon Closure value  = + 0.5"
Correction value = + 0.25"

Final Direct Angle value: **3-0-06.9**
Final Close Angle value: **356-59-53.1**

## 5-4.  Distance Observations

*a. General.*  Distances of 10 m or less can be measured with a steel or invar tape.  Distances of 30 m or less can be measured with a tensioned steel tape, invar tape (or invar wire that can be attached to the steel bolt or insert directly), a subtense bar, or an EDM.  An EDM is the preferred instrument for distances beyond 30 m.  Microwave based EDM systems shall not be used.

*b. Distance measurement with a tape.*  Distances measured between monuments will be made point-to-point whenever possible.  If unable to measure point-to-point, a tripod and theodolite will be plumbed and leveled over the points and the distance measured between the trunnion axis of the setup.  If tensioned equipment is used, the uncorrected distance should be measured to 0.01 mm.  Distance measurements by tape will be independently made at least two times by repeating the required setup.  When a mean uncorrected distance is determined using a steel tape, invar tape, or invar wire measuring unit,  the following corrections will be applied, when appropriate, to determine true distance.

(1) Temperature correction.  The correction for thermal expansion of steel tapes between the observed and standardized tape distance (ignore if using an invar tape) will be:

$$dL = k_a \cdot L \cdot ( T - T_o )$$

(Eq 5-2)

where

$k_a = 0.0000116$
$L$ = measured length (m)
$T$ = measured ambient temperature (°C)
$T_o$ = standardized temperature (°C)

(2) Tension correction.  The tension correction between the observed and standardized tape distance will be:

$$dL = ( P - P_o ) ( L ) / ( a ) ( E )$$

(Eq 5-3)

where

$P$ = applied tension (kg)
$P_o$ = standardized tension (kg)
$L$ = measured length (m)
$a$ = cross-sectional area of tape (cm$^2$)
$E = 2.1 \cdot 10^{-6}$

(3) Sag correction.  The correction due to the unsupported length(s) of the tape will be:

$$dL = ( w^2 ) ( L^2 ) / ( 24 ) ( P^2 )$$

(Eq 5-4)

where

$w$ = weight of tape per unit length (kg/m)
$L$ = distance between supports (m)
$P$ = applied tension (kg)

(4) Slope correction.  The slope distance and height difference correction if applicable will be:

$$H = \text{sqrt} \ ( S^2 - dH^2 )$$

(Eq 5-5)

where

$H$ = horizontal distance
$S$ = slope distance
$dH$ = height difference

(5) Standardized tape.  The correction due to calibrated standardization error will be:

$$dL = \text{true length} - \text{nominal length}$$

*c. Distance measurement with a subtense bar.*  If measuring the distance with a subtense bar, the subtense bar and theodolite will be plumbed and leveled over the points defining each end of the line of observation as described in the previous paragraphs.  The optical sight will be used to set the subtense bar perpendicular to the line of observation.  The angle subtended by the subtense bar will be measured with four independent sets by the theodolite.  Record the height of the instrument and height of the target to at

least one (1) mm for later reduction of the point-to-point distance. Procedures for angle and direction setups will be followed for optical theodolites.

## 5-5. Electro-Optical Distance Measurement



**Figure 5-2. EDM observations at control structure in Central & Southern Florida Flood Control Project. EDM force-centered in concrete pedestal at external reference point. (Jacksonville District and Arc Surveying & Mapping, Inc.)**

*a. General.* If measuring the distance with an EDM, including those incorporated within total stations, the instrument will be accurately plumbed and leveled over the point, or force-centered in a monument as shown in Figure 5-2.

*b. Specifications.* The following specifications are provided for making EDM distance observations:

(1) Warm-up period. Prior to its use, an EDM should be allowed to "warm up" according to manufacturer specifications. An EDM should be operated with fully charged batteries in the manufacturer recommended range of operating temperatures.

(2) Signal strength. Prior to measurements with the EDM, the target prism will be set perpendicular to within 10 deg of the line-of-sight. Distances will be measured after electronic pointing has yielded a maximum signal strength return. If necessary, the prism will be adjusted to maximize the strength of the signal.

(3) Repetitions. EDM measurements made to target point reflectors will be repeated at least three (3) times by re-setting and re-pointing the EDM instrument and performing the observation. Five separate distance readings for each pointing will be recorded to determine their mean value.
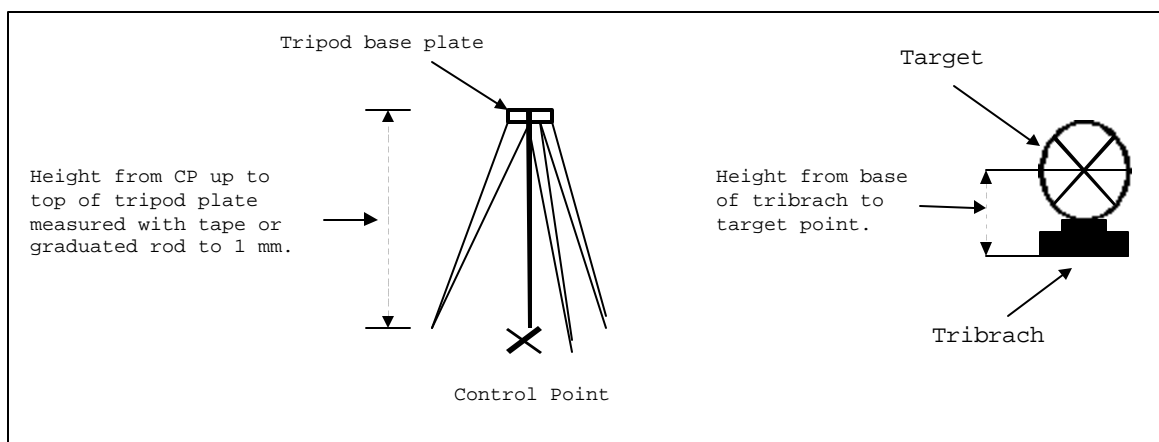
**Figure 5-3. Reference points to measure height of target or GPS antenna height. A vertical height is measured between the ground control point (CP) and the top surface of the tripod base plate. The distance between the bottom of the tribrach and the center of the target is added to the height of the tripod base plate to determine the height of target. For GPS antennas, the manufacturers L1 phase center offset value as specified from the antenna base is added to the height measured from the base of the tribrach to the top of the tribrach/antenna mounting adapter**

(4) Reading precision. Repeated observations will be recorded to the least count on the EDM or to the nearest 0.001 or 0.0001 meter. The mean result will be recorded to the same degree of precision.

(5) Forward distances. Distances will be observed in one direction when the instrument is set up on positive centered concrete instrument stands. If required, measurements in both directions will be made between fixed instrument stands or when using tripod supports if the one-way distance deviated over 5 mm from previous survey observations.

(6) Meteorological data. Barometric pressure, dry bulb temperature, and wet bulb temperature will be measured at the instrument stations and at the target station.

*(a)* Temperature and pressure will be measured in a location shaded from the sun, exposed to any wind, at least 5 feet above the ground, and away from the observer and instrument.

*(b)* Barometers shall be capable of 2 mm mercury precision or better (record pressure to 1 mbar).

*(c)* Thermometers and psychrometers will be capable of 1 degree Celsius precision or better (record temperature to nearest $1^\circ$C).

*(d)* A zero (0) ppm value for refraction will be entered into the EDM instrument when refractive index corrections are calculated using the formulas listed in Section 5-7.

(7) Instrument-Reflector combinations. An EDM instrument must be paired with a specific (numbered) reflector. Only one instrument/reflector combination shall be used for a particular line. The serial numbers of the instrument and reflector shall be recorded for each observation to verify this fact.

(8) Eccentricity observations. These offset measurements shall be made for each EDM distance.

*(a)* The height of EDM and height of prism will be measured to 1 mm, and similarly for the theodolite and target if used--see Figure 5-3.  Some prism assemblies may be adjusted for lateral eccentricities, as shown in Figure 5-4.

*(b)* Engineer scales or pocket tape is used for measuring instrument/reflector heights over base.

*(c)* Instrument stands with elevations determined relative to domed plugs must be corrected when HI measurements are relative to the plug base.

*(d)* The EDM instrument shall have the mechanical center marked such that accurate instrument heights may be determined for each observation.  The center of the reflector shall be similarly marked.
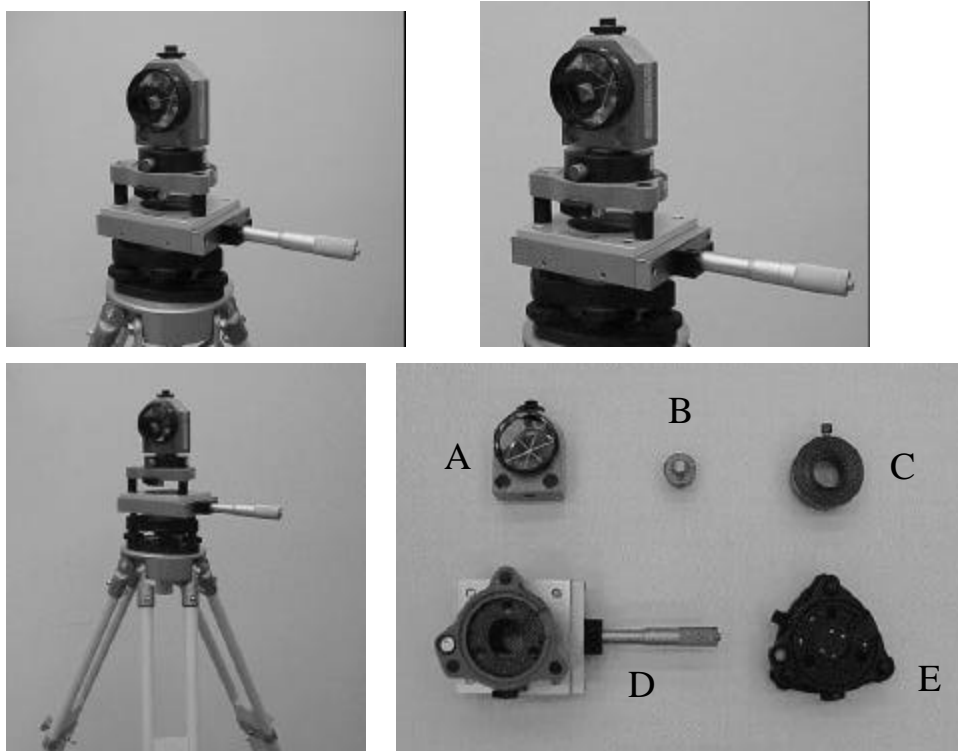


**Figure 5-4.  Typical EDM reflector mounted in precision adjustable tribrach.  Reflector (A), 5/8-11 Adapter (B), Adapter ring (C), Translation Stage (D), Tribrach (E) used for alignment-offset measurements**

(9) Instrument/prism constant.  For each EDM/prism combination used, the calibration constant shall be recorded in the field book for each observation.  Accordingly, the instrument and reflector serial numbers also must be noted in the field book.  Incorrect instrument/reflector serial numbers or constants will result in rejection of all data.

(10) Instrument scale factor.  The constant scale factor for EDM distances shall be recorded in the field book for each survey.  Accordingly, the instrument serial number must be noted in the field book.

## 5-6. EDM Reductions

*a. Field corrections.* Horizontal distances will be computed and verified/checked in the field against previously surveyed values with the application of the following corrections and constants.

(1) Instrument/Prism Constant.
(2) Horizontal and Vertical Eccentricities.
(3) Slope-to-Horizontal Correction.
(4) Scale Factor.
(5) Refraction correction

No corrections to sea level need be applied in projects involving short lines (i.e., less than 1000 m) or projects near sea level. For horizontal distances, slope distances shall be reduced using the elevation differences determined from differential levels. Field notes and computation/reduction recording forms shall show the application and/or consideration of all the correction factors described above.

*b. Tolerances.* The spread from the mean of the observations (3 sets of 5 readings each) shall not exceed 0.002 meters, or else re-observe the series. Measurements taken in both directions should agree to 0.002 meter after measurements are corrected for slope and atmospheric refraction, as required. If the distances are not rejected, a single uncorrected distance will be computed as the mean of the three independent distance measurements.

*c. Distance reductions.* Three dimensional mark-to-mark spatial straight line distances will be computed for use in network adjustments based on the following corrections.

(1) Refraction correction. EDM Distances will be corrected for atmospheric refraction using standard reduction formulas. A determination of the refractive index correction for ambient atmospheric conditions will be made based on meteorological data collected on-site.

(2) Additive constant. Zero error corrections determined from instrument/reflector calibration will be applied to distances measured with a particular EDM and prism combination.

(3) Scale error. Correction for EDM frequency scale error will be applied to the EDM distances.

(4) Geometric corrections. Instrument to station eccentricities will be eliminated for both stations using corrections for EDM, prism, theodolite, and target heights.

## 5-7. Atmospheric Refraction Correction

*a. General.* EDM distances must be corrected for the actual refractive index of air along the measured line. Measurement of atmospheric conditions at several points along the optical path must be performed with well calibrated thermometers and barometers in order to achieve the 1 ppm accuracy. If the meteorological conditions are measured only at the instrument station (usual practice), then errors of a few parts per million may occur, particularly in diversified topographic conditions. In order to achieve the accuracy better than 1 ppm, one must measure meteorological conditions every few hundred meters (200m - 300m) along the optical path.

PROJECT
PICES: HORIZONTAL EDM OBS    PAGE __ OF __   COMPUTED BY  Bergen   DATE 27 July 84

SUBJECT
TYPICAL FIELD BOOK DATA & COMPUTATIONS    CHECKED BY  Noles   DATE 27 July 84

THE FOLLOWING DATA MUST BE FIELD RECORDED/COMPUTED FOR EACH PICES EDM OBSERVATION. NO RIGID RECORDING FORMAT IS SPECIFIED. (THE SAMPLE OBSERVATION IS TOTALLY SIMULATED.)

|  | ^ CFBC 992 | φ CFBC 993 | 27 July 1984 INGLIS Lock (Full @ 36.3) |
|---|---|---|---|
| MARK | Instrument Stand | TRIPOD | CLEAR |
| Instrument | AGA # XXXX | REF S/N XXX | ^ - Noles |
|  |  |  | 0 - Bergen |
| Elevation | 99.2198' m | 97.6147' m | φ - Bergen |
| Plug Insert Office | -0.051' m | n/a | Check - Noles |
| HI (ft)/m | (0'.73) + 0.226' m | (5'.62) + 1.713' m | T - 0847 AM |
| Elevation  ^ | 99.3948' m | φ  99.3277' m |  |

| | Set 1 | Set 2 | Temp (°F) | Press (in Hg) |
|---|---|---|---|---|
| | 72.1084 m | 72.1086 m | | |
| | .1087 | .1087 | ^ 86/87 | 30.12/30.15 |
| | .1081 | .1088 | φ 85/86 | |
| | .1083 | .1085 | M 86 | 30.1 in Hg' |
| | 72.1085 | 72.1083 | | |
| Mean (set) | 72.1084' | 72.1086' | +16' ppm Dialed in AGA | |

Mean of Sets   72.108 m'    MET Corrected Slope Distance
              -0.002 m'    System Constant (AGA # XXXX Ref/SN XXX)
                                  - 8 June 84 Calibration

              72.106 m'    Corrected Slope Distance (T)

                           Δ elev = 0.0671' m

Corrected Horizontal Distance: $H = (T^2 - \Delta_e^2)^{1/2} = 72.106'$ meters

HAD A REFLECTOR ROD BEEN USED THEN ITS SERIAL NUMBER WOULD HAVE BEEN RECORDED

**Figure 5-5.  Typical field EDM recording form--Inglis Lock, Cross Florida Barge Canal (Jacksonville District)**

*b.  Field ppm corrections.*  Distance reductions that employ a "parts-per-million" (ppm) correction for atmospheric refraction are useful for preliminary checks on the distance data--see example at Figure 5-5.  The effective ppm value can be dialed into the instrument, but it is not recommended because final reductions for atmospheric refraction should be made using rigorous formulas, which requires a zero (0) value for ppm to be entered during measurement.  A field check can still be made by

finding the appropriate ppm correction value and applying this numerically to the distance recorded in the field book (instead of within the instrument).

$$D_{CORR} = [\ (ppm / 1 \cdot 10^{6}\ )\ (D_{MEAS})\ ] + D_{MEAS}$$

<div align="right">(Eq 5-6)</div>

where

    $D_{CORR}$ = field corrected distance
    ppm = parts per million term
    $D_{MEAS}$ = measured distance set with zero ppm

Distance checks in the field are made by comparing the ppm corrected measurements to the corrected results from previous observation campaigns. Ppm correction values are supplied by look-up tables or simple nomogram type graphs that are specific to each instrument. Ppm methods only give approximate refraction correction values based on local temperature and pressure measurements.

    *c. Measurement of temperature and pressure.* When greater accuracy in distance measurement is required, temperature, pressure, and relative humidity measurements are critical for calculating a rigorous refractive index correction. One should always use rigorous formulas to calculate the refractive index correction rather than diagrams or simplified calculation methods supplied by the manufacturers.

    (1) Pressure. Pressure should be measured with a barometer at both ends of the line. The mean of the two values is used in the refractive index correction equation. If it is not possible to place barometers at both ends of the line, place a barometer at the instrument end, and use the elevations of the two ends together with the pressure measured at the instrument to calculate the pressure at the other end.

    (2) Temperature. Temperature should be measured with a psychrometer at both ends of the line. The mean of the two values is used in the refractive index correction equation. It is more difficult to properly measure temperature. Thermometers must be well shielded from the sun's radiation by enclosing in a reflective insulating shield. However, this permits heat to build up within the shield, and thus a small fan or some other means must be used to move air over the temperature sensing device so that the true air temperature is read. Measurements near the ground can be a poor indication of the true temperature.

    (3) Relative humidity. The influence of relative humidity is important in the highest precision measurements. Psychrometers with wet and dry thermometers should be used to determine correction components for water vapor content.

    *d. Refractive index correction formulas.* Distance reduction calculations for determination of the refraction (first velocity) correction for precise electro-optical distance measurements are presented below. The formulas and derivations are developed fully in Rueger, 1990--see Appendix A. The refraction correction is as follows:

$$d = (n_R / n_L)\ d_{MEAS}$$

<div align="right">(Eq 5-7)</div>

where

    $d$ = corrected distance
    $n_L$ = ambient refractive index
    $n_R$ = reference refractive index
    $d_{MEAS}$ = measured distance

The reduction is essentially an application of the scale factor ($n_R$ / $n_L$) to the measured distance. The scale factor relates the instrument reference refractive index to the refractive index based on ambient atmospheric conditions. The ambient refractive index ($n_L$) is:

$$n_L = 1 + [ (A + B) / (1 \cdot 10^{8}) ]$$

(Eq 5-8)

where

$$A = \{ [ E1 \cdot (E2 / E3) ] + [ E4 \cdot (E5 / E6) ] \} \cdot D_S$$

E1 = 1646386.0
$E2 = 238.0185 + \sigma^2$
$E3 = ( 238.0185 - \sigma^2 )^2$
E4 = 47729.9
$E5 = 57.362 + \sigma^2$
$E6 = ( 57.362 - \sigma^2 )^2$

$$B = [ F1 + F2 - F3 + F4 ] \cdot D_W$$

F1 = 6487.31
$F2 = 174.174 \, \sigma^2$
$F3 = 3.55750 \, \sigma^4$
$F4 = 0.61957 \, \sigma^6$

$$D_S = ( P_S / T ) \cdot [ 1 + P_S \cdot (G1 - (G2 / T) + (G3 / T^2) ) ]$$

$G1 = 57.90 \cdot 10^{-8}$
$G2 = 9.325 \cdot 10^{-4}$
G3 = 0.25844

$$D_W = (P_w / T) \cdot [ 1 + P_w \cdot ( 1 + ( H1 \cdot P_w ) ) \cdot H2 ]$$

$H1 = 3.7 \cdot 10^{-4}$
H2 = H3 + H4 - H5 + H6
$H3 = -2.37321 \cdot 10^{-3}$
H4 = 2.23366 / T
$H5 = 710.792 / T^2$
$H6 = (7.75141 \cdot 10^{-4}) / T^3$

where

$\sigma = 1/\lambda$
$\lambda$ = instrument carrier wavelength, (in micrometers),
$D_S$ = density factor of dry air
$D_W$ = density factor of water vapor
P = total atmospheric pressure (mbar)
$P_w$ = partial water vapor pressure (mbar)
$P_S = (P - P_w)$ = partial pressure of dry air (mbar)
T = Temperature in Kelvin (K) = (273.15 + t)
t = temperature in Celsius (°C)

The reference refractive index value ($n_R$) is obtained from the manufacturer's specifications for a given EDM instrument. Water vapor pressure ($P_w$) is determined by the difference between wet and dry bulb (psychrometer) temperatures as follows:

$$P_w = ep - [ ( 0.000662 ) ( P ) ( t_D - t_w ) ]$$

where

$P$ = pressure (mb)
$t_D$ = dry bulb temperature (°C)
$t_w$ = wet bulb temperature (°C)
$ep = ( C + D ) ( E ) \exp ( F / G )$
$C = 1.0007$
$D = ( 3.46 \cdot 10^{-6} ) ( P )$
$E = 6.1121$
$F = ( 17.502 ) ( t_w )$
$G = ( 240.97 ) + ( t_w )$

*e. Reference line ratio methods.* Using a special observing procedure, one may account for the influence of refraction without explicit use of temperature and pressure measurements. Corrections are obtained by using the ratio of a measured and a known distance to find the effective scale change due to refraction. These procedures are described in Chapter 10.

*f. Summary data sheets.* A summary data sheet for EDM distance observations is shown in Figure 5-6 on the following page.

## 5-8. Mandatory Requirements

The corrections and calibrations to observed distance measurements are considered mandatory.

| | INSTRUMENT @ **CDM - 2** DISTANCE TO: | INITIAL DISTANCE **JUNE 1991** | 40 TH READING **DEC 1996** | CHANGE (MTRS) | CUM. CHANGE (MM) | 41 ST READING **JAN 1997** | CHANGE (MTRS) | CUM. CHANGE (MM) | 42 ND READING **APR 1998** | CHANGE (MTRS) | CUM. CHANGE (MM) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 692.9998 | SSRM 1 | 692.9890 | 693.0005 | 0.0007 | 11.5 | 693.0008 | 0.0003 | 11.8 | 692.9964 | -0.0044 | 7.4 |
| 719.7269 | SSRM 2 | 719.7209 | 719.7268 | -0.0001 | 5.9 | 719.7289 | 0.0021 | 8.0 | 719.7220 | -0.0069 | 1.1 |
| 678.0597 | SSRM 3 | 678.0380 | 678.0600 | 0.0003 | 22.0 | 678.0609 | 0.0009 | 22.9 | 678.0543 | -0.0066 | 16.3 |
| 705.4121 | SSRM 4 | 705.3855 | 705.4121 | 0.0000 | 26.6 | 705.4131 | 0.0010 | 27.6 | 705.4045 | -0.0086 | 19.0 |
| 732.8935 | SSRM 5 | 732.8772 | 732.8930 | -0.0005 | 15.8 | 732.8943 | 0.0013 | 17.1 | 732.8868 | -0.0075 | 9.6 |
| 760.6852 | SSRM 6 | 760.6642 | 760.6853 | 0.0001 | 21.1 | 760.6854 | 0.0001 | 21.2 | 760.6812 | -0.0042 | 17.0 |
| 788.1278 | SSRM 7 | 788.1400 | 788.1269 | -0.0009 | -13.1 | 788.1284 | 0.0015 | -11.6 | 788.1203 | -0.0081 | -19.7 |
| 668.2854 | SSRM 8 | 668.2606 | 668.2853 | -0.0001 | 24.7 | 668.2841 | -0.0012 | 23.5 | 668.2821 | -0.0020 | 21.5 |
| 696.0971 | SSRM 9 | 696.0571 | 696.0975 | 0.0004 | 40.4 | 696.0979 | 0.0004 | 40.8 | 696.0945 | -0.0034 | 37.4 |
| 723.9291 | SSRM 10 | 723.9081 | 723.9281 | -0.0010 | 20.0 | 723.9297 | 0.0016 | 21.6 | 723.9176 | -0.0121 | 9.5 |
| 751.7767 | SSRM 11 | 751.7551 | 751.7761 | -0.0006 | 21.0 | 751.7763 | 0.0002 | 21.2 | 751.7680 | -0.0083 | 12.9 |
| 779.7186 | SSRM 12 | 779.7121 | 779.7182 | -0.0004 | 6.1 | 779.7188 | 0.0006 | 6.7 | 779.7114 | -0.0074 | -0.7 |
| 663.9446 | SSRM 13 | 663.9126 | 663.9447 | 0.0001 | 32.1 | 663.9446 | -0.0001 | 32.0 | 663.9399 | -0.0047 | 27.3 |
| 691.9190 | SSRM 14 | 691.8944 | 691.9176 | -0.0014 | 23.2 | 691.9192 | 0.0016 | 24.8 | 691.9113 | -0.0079 | 16.9 |
| 719.8884 | SSRM 15 | 719.8851 | 719.8881 | -0.0003 | 3.0 | 719.8877 | -0.0004 | 2.6 | 719.8810 | -0.0067 | -4.1 |
| 664.6144 | SSRM 16 | 664.5753 | 664.6148 | 0.0004 | 39.5 | 664.6150 | 0.0002 | 39.7 | 664.6086 | -0.0064 | 33.3 |
| 692.6458 | SSRM 17 | 692.6186 | 692.6448 | -0.0010 | 26.2 | 692.6468 | 0.0020 | 28.2 | 692.6400 | -0.0068 | 21.4 |
| 720.5207 | SSRM 18 | 720.5187 | 720.5204 | -0.0003 | 1.7 | 720.5215 | 0.0011 | 2.8 | 720.5158 | -0.0057 | -2.9 |
| 670.9071 | SSRM 19 | 670.8744 | 670.9073 | 0.0002 | 32.9 | 670.9075 | 0.0002 | 33.1 | 670.9017 | -0.0058 | 27.3 |
| 698.6566 | SSRM 20 | 698.6312 | 698.6568 | 0.0002 | 25.6 | 698.6555 | -0.0013 | 24.3 | 698.6511 | -0.0044 | 19.9 |
| 675.0941 | SSRM 21 | 675.0642 | 675.0948 | 0.0007 | 30.6 | 675.0947 | -0.0001 | 30.5 | 675.0878 | -0.0069 | 23.6 |

CERRILLOS DAM MONITORING
SPILLWAY POINTS
HORIZONTAL REFERENCE POINT READINGS

**Figure 5-6.  Data sheet for periodic distances to fixed points on spillway.  42 observations made during period 1990 through 1998--only last three tabulated in report.  Note some monitor points have moved some 3 to 4 cm since initial construction of the dam.  Cerrillos Dam, Puerto Rico (Jacksonville District).**